Devils Lake Wetland Restoration Modeling

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Abstract

Since 1992 Devils Lake, a terminal lake in North Dakota, has risen nearly 7.8 meters (25.7 feet), flooding an additional 362 square kilometers (sq. km.) (140 square miles (sq. mi.)). In July 2001, the lake reached a peak elevation of 441.44 meters (1448.3 feet) above mean sea level, with a corresponding surface area of 540 sq. km. (209 sq. mi.). As part of the flood damage reduction study, a comprehensive, impact analysis on Devils Lake elevations was done of restoring wetlands in the upper basin. WEST Consultants did this study under contract. The study included extensive use of available GIS information, including USGS digital elevation data, the National Wetland Inventory and NRSC soil data. The study initially used HEC-HMS with the soil moisture accounting procedure but found that program was not adequate for detailed evaluation of wetland restoration. The contractor then wrote a new hydrologic modeling program, **PRINET**, to do the evaluation. The WMS program was considered but was not felt to be the appropriate tool for modeling a basin as large as this. The entire 2,616 square mile upper Devils Lake drainage basin containing approximately 63,458 intact wetlands was divided into 9,078 subbasins and calibrated to the period of record Devils Lake inflows. Of the 52,210 possibly drained wetlands, 13,464 were assumed restorable. Various restoration alternatives and future climate scenarios were modeled to determine the impact of restoration on inflows to Devils Lake and resultant lowering of lake levels.

Introduction

WEST Consultants, INC., and Polaris Group, Inc conducted the Devils Lake Upper Basin Storage Evaluation for the U.S. Army Corps of Engineers, St. Paul District. The primary purpose of this study is to assess the impacts of upper basin storage restoration alternatives on the inflows to Devils Lake. **Figure 1** shows the Devils Lake Drainage basin. The upper basin storage alternative under consideration is the restoration of "drained" depressions. A vast amount of geographic and historical data was collected to (1) delineate and classify the depressions, and (2) develop a physically based hydrologic model to simulate the hydrologic functions of the depressions.

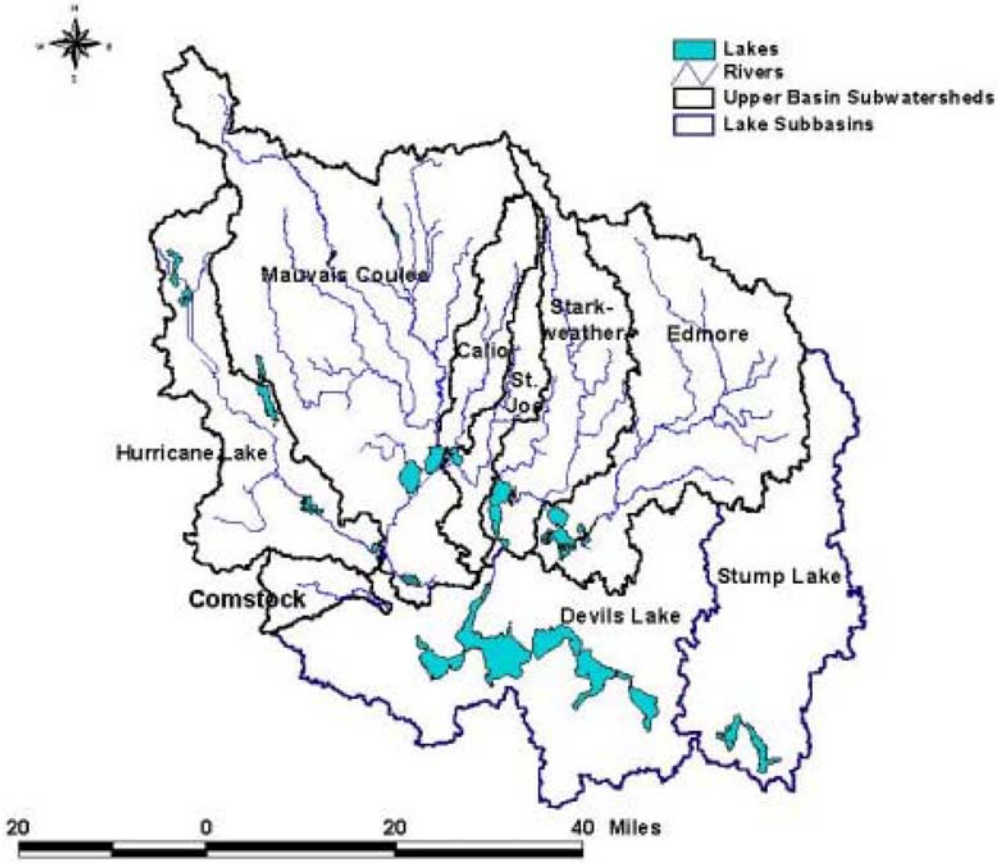

Figure 1. Devils Lake Drainage Basin

Given the limitations in the available data and other project constraints, some simplifications and assumptions were made during the analysis. These assumptions were appropriate given the objective and time constraints of this study. Since the results of this study indicate that depression restoration can reduce the volume of runoff entering Devils Lake, further studies should be conducted to more accurately quantify the runoff reduction resulting from depression restoration. A summary of the results and recommendations for future studies are presented in the following sections.

Depression Delineation and Classification

Depressions were delineated and classified for the entire 2,616 square mile upper basin watershed (exclusive of Stump Lake and local Devils Lake drainage area). A digital elevation model (DEM) was used to determine the location, area, and volume of depressions in the upper basin subwatersheds. Using the flow chart shown in **Figure 2**, the depressions were categorized as *possibly intact*, *possibly drained*, *lake* or *other* based on aerial photos, National Wetlands Inventory (NWI) data, flow direction data, and digital quad maps. The modifier "possibly" was added to the

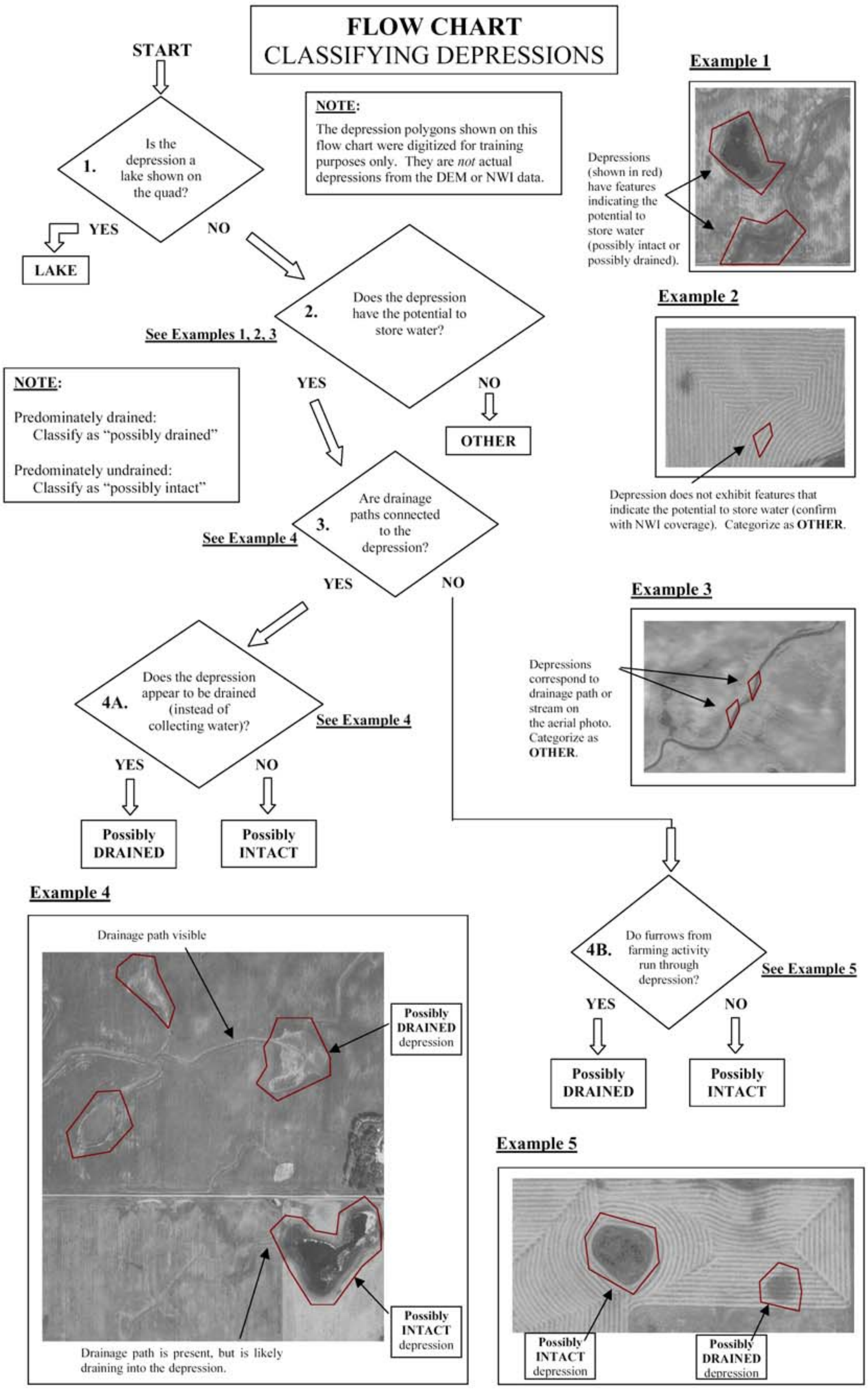

Figure 2. Flow Chart - Classifying Depressions

"intact" and "drained" classifications because field verification was not performed during this study. Depressions that were not captured by the DEM were added and classified based on the aerial photos and NWI data. It should be noted that the NWI wetland definition and the resulting NWI polygons do *not* include depressions that were completely drained prior to 1979. Therefore, any completely drained depressions not captured by the DEM nor by the NWI data are not incorporated into the data set. The average depth (and volume) for each of the non-DEM depressions was estimated based on an average depth-area relationship developed from all of the DEM-derived depressions. A comprehensive quality assurance review of the classified depressions was conducted for the entire upper basin. The results of the classifications were compared to previous studies.

The depressions described as "possibly drained" in this report may be fully drained, mostly drained, partially drained, likely drained (i.e., appears drained, but not definitively so), filled-in, or otherwise non-intact or non-functional. The clear presence of a man-made drain was not a prerequisite for classifying a depression as "possibly drained". In a similar manner, depressions labeled as "possibly intact" could be fully intact, mostly intact, or likely intact (i.e., appears intact, but not definitively so). The presence of standing water was not a prerequisite for classifying a depression as "possibly intact" because water in a shallow depression could be fully lost to evaporation. **Figure 3** shows the result of the classified depressions. A summary of the possibly intact and possibly drained depressions identified in this study is included in **Table 1.**

Due to the comprehensive nature of the depression delineation and classification process, the results given in the above table represent very reasonable estimates of upper basin depression area and volume. Overall, however, the estimates of intact and drained depression area and volume totals are believed to be conservative (i.e., underestimated) to some degree for the following reasons: (1) the added NWI polygons do not represent the maximum depression area; (2) a number of DEM depression polygons appeared to be smaller in area than the corresponding depressions on the aerial photos (The underestimated area and volume from the DEM was only partly offset by the presence of larger-than-appropriate DEM depression polygons); and (3) there were areas, especially within the 10-foot contour interval region, where depressions were missed by both the DEM grid and the NWI data set. For these reasons, it is likely that a more intensive analysis would result in a greater number of depressions.

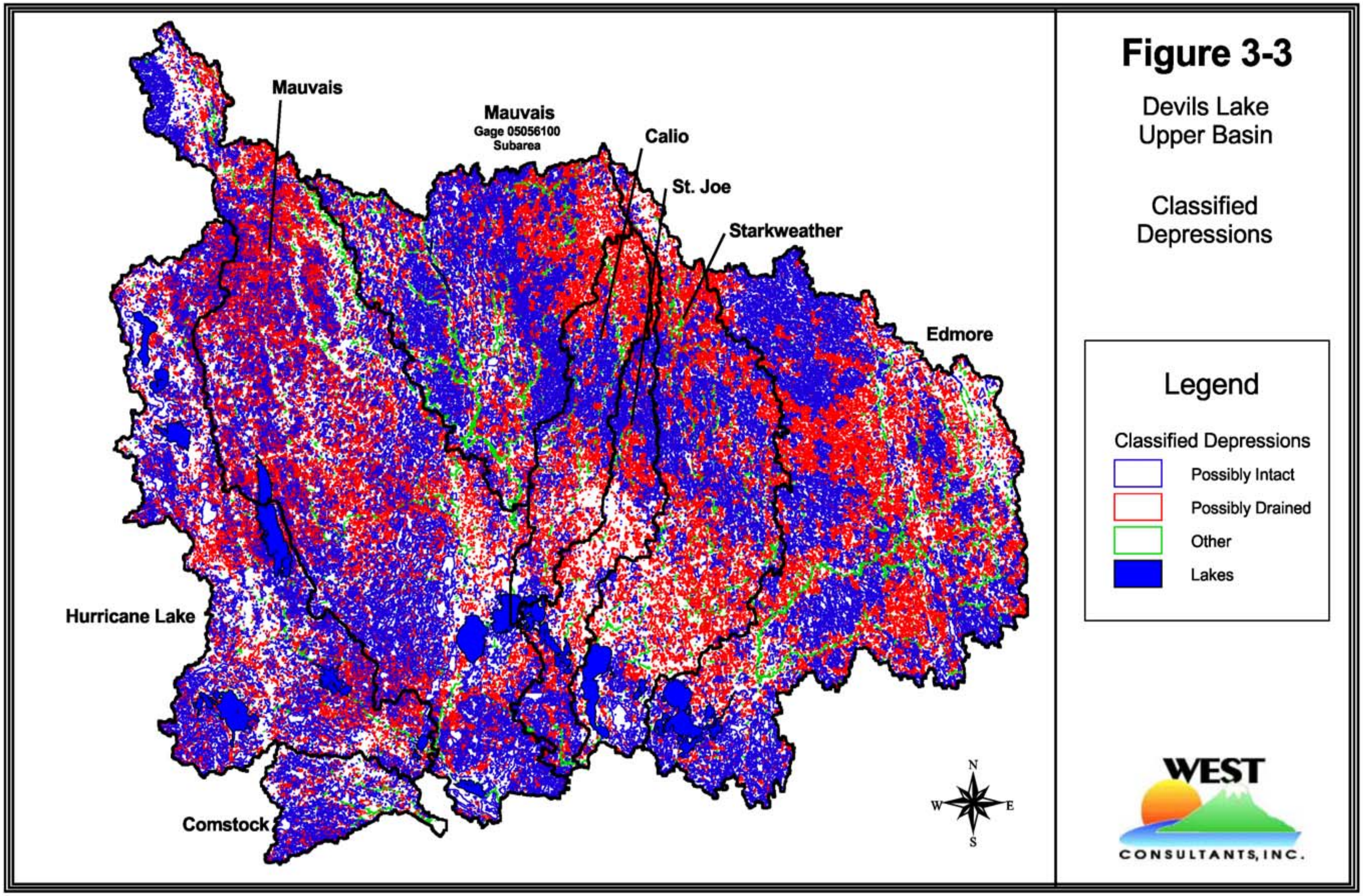

Figure 3. Classified Depressions

Table 1. Possibly Intact and Possibly Drained Wetlands

Depression Type	Count	Area (acres)	Volume (acre-ft)
Possibly Intact [1, 2]	63,458	201,990	481,604
Possibly Drained [1, 3]	52,210	92,429	132,729
Total	115,668	294,419	614,333

Notes:

(1) Based upon the available data and classification procedure, these depressions were classified as either "intact" or "drained". However, because field verification was not performed, the modifier "possibly" was adopted.

(2) "Possibly intact" depressions may be fully intact, mostly intact, or likely intact (i.e., appears intact, but not definitively so). The presence of standing water was not a prerequisite for classifying a depression as "possibly intact" because water in a shallow depression could be fully lost to evaporation.

(3) "Possibly drained" depressions may be fully drained, mostly drained, partially drained, likely drained (i.e., appears drained, but not definitively so), filled-in, or otherwise non-intact or non-functional. The clear presence of a man-made drain was not a prerequisite for classifying a depression as "possibly drained".

Although the depression delineation and classification conducted during this study were extensive and detailed, there were some limitations to the methods. These limitations, with varying degrees of importance, include the following: (1) no field verification was conducted due to time constraints and the presence of snow cover during the study period; (2) partial drainage was not accounted for; (3) some individual depression classifications are subject to interpretation; (4) classification was based upon aerial photos representing one point in time; (5) a small number of the aerial photos were darker than normal, making the depressions more difficult to categorize; and (6) the resolution of the aerial photos was not fine enough to identify the location of fully drained depressions not captured by the DEM nor the NWI data and the location of some of the drainage ditches.

While there are some limitations to the classification process, there are also a number of important advantages of this classification process, including: (1) depressions were individually delineated and classified over the entire upper basin watershed; (2) physically-based delineation was conducted using the DEM, thus minimizing the need for extrapolation; (3) visual verification of depressions using aerial photos was utilized; (4) supplementary data (NWI, quad maps, flow direction) was incorporated; and (5) quality assurance/quality control was performed.

The accuracy of the delineation and classification of some of the individual depressions was limited by the available data and project constraints. For future studies, it is recommended that this work be refined as follows:

- Obtain historical aerial photos, preferably from the 1950's when drainage activity was minimal, to assist in identifying depressions in those areas missed both by the DEM grid and NWI data. These historical photos could also be compared to current photos to verify the depression classification.

- Perform extensive field verification to locate drainage ditches, determine the functionality of the farmed depressions, and verify the depression classification.

- Utilize the 1997 color infrared photography, which is higher resolution than the DOQ's used in this study, to refine the depression delineation and classification, but this would be very labor intensive because the data is not available in digital format.

- Obtain more refined soil data to develop relationships between depression area and hydric soils.

- Include more classifications such as "partly drained". Separate depressions that have drainage ditches from those that have been disturbed by other activities such as farming.

- Obtain higher resolution digital terrain data, especially in those areas currently modeled from the 10-foot contour interval data.

Hydrologic Model

A number of hydrologic models were surveyed and evaluated for use in simulating the water mass balance of the watershed to include existing depressions and with-project restored depression conditions. The Watershed Modeling System (WMS) was considered but not selected because it did not have a snowmelt algorithm for interannual simulation, required a small time interval to model each cell for a duration of 20 years over a large watershed, did not have a database management system to handle the vast amounts of data, and was unstable to run initially. Originally, the hydrologic model of the Devils Lake basin was going to be developed using the HEC Hydrologic Modeling System (HEC-HMS), Version 2.1.1 (Hydrologic Engineering Center, U.S. Army Corps of Engineers, 2001). However, it was determined that the HEC-HMS model could not reasonably be configured to adequately model the hydrologic function of the depressions for the following reason:

- The Soil Moisture Accounting (SMA) algorithm does not adequately simulate the hydrologic function of the depressions. All depressions are lumped into one depression over an entire subbasin. This prevents a subbasin from discharging at its outlet until all of the depression volume is utilized. It also over-estimates the net evaporation from the subbasin by spreading the surface area over the entire subbasin. It consequentially, prevents any evapotranspiration from the soil until the depressions are dry. After initial trials, it was clear that this method over-predicted the capture of depression storage and, therefore, could not be used to analyze upper basin storage in the Devils Lake basin.

- Reservoir elements could be used to model the depression storage. However, HEC-HMS does not apply precipitation or evaporation to the reservoir elements. Therefore, additional subbasin elements and diversion element would need to be added to account for precipitation and evaporation on the reservoirs. The elements and associated inputs must be input manually into HEC-HMS. The average subbasin size is one square mile, with a total of 2,618 subbasins. Manual model construction was extremely time consuming for a hydrologic model of this magnitude and was not feasible under the project time constraints.

- HEC-HMS does not have a frozen ground algorithm. Since snowmelt is a major component of the annual runoff in the Devils Lake basin, a method had to be developed to simulate snowmelt on frozen ground. Two HEC-HMS models were set up for each subwatershed to simulate frozen ground and unfrozen ground conditions. Therefore, because of the manual entry of data into the models, and inefficiency of starting/stopping the simulations to utilize different HEC-HMS models and capture the starting and ending states, the HEC-HMS modeling could not be completed within the project's time limit.

Because of these limitations and difficulties, HEC-HMS, in essence, had to be programmed from the outside, and tricked into modeling the processed in the Devils Lake basin. Consequently, a custom hydrologic, a custom hydrologic model, the Pothole-River Networked Watershed Model **(PRINET**), was developed to simulate the depression storage, soil storage, and runoff in the Devils Lake basin. The **PRINET** application was written in Microsoft Visual Basic 6.0 (Visual Basic For Applications) inside a Microsoft Access database. The model used geographic data to develop the drainage patterns and subbasins. Most of the hydrologic calculations use the same algorithms as HEC-HMS.

Six subwatersheds, encompassing the upper basin of Devils Lake, were modeled by **PRINET** as shown in **Figure 4**. **Figure 5** shows a flow chart of the model. Each subwatershed was divided into numerous subbasins.

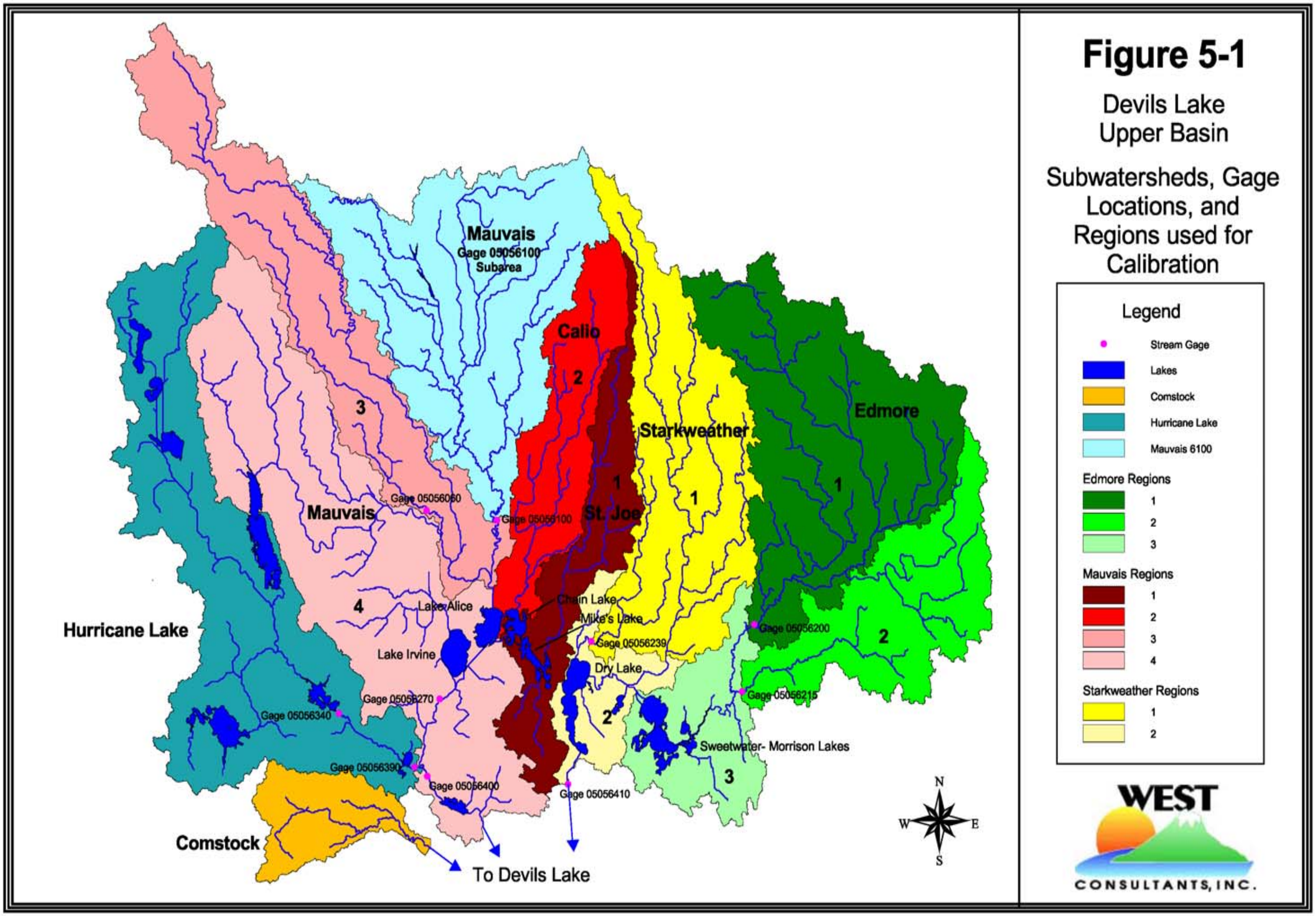

Figure 4. Devils Lake Subwatersheds

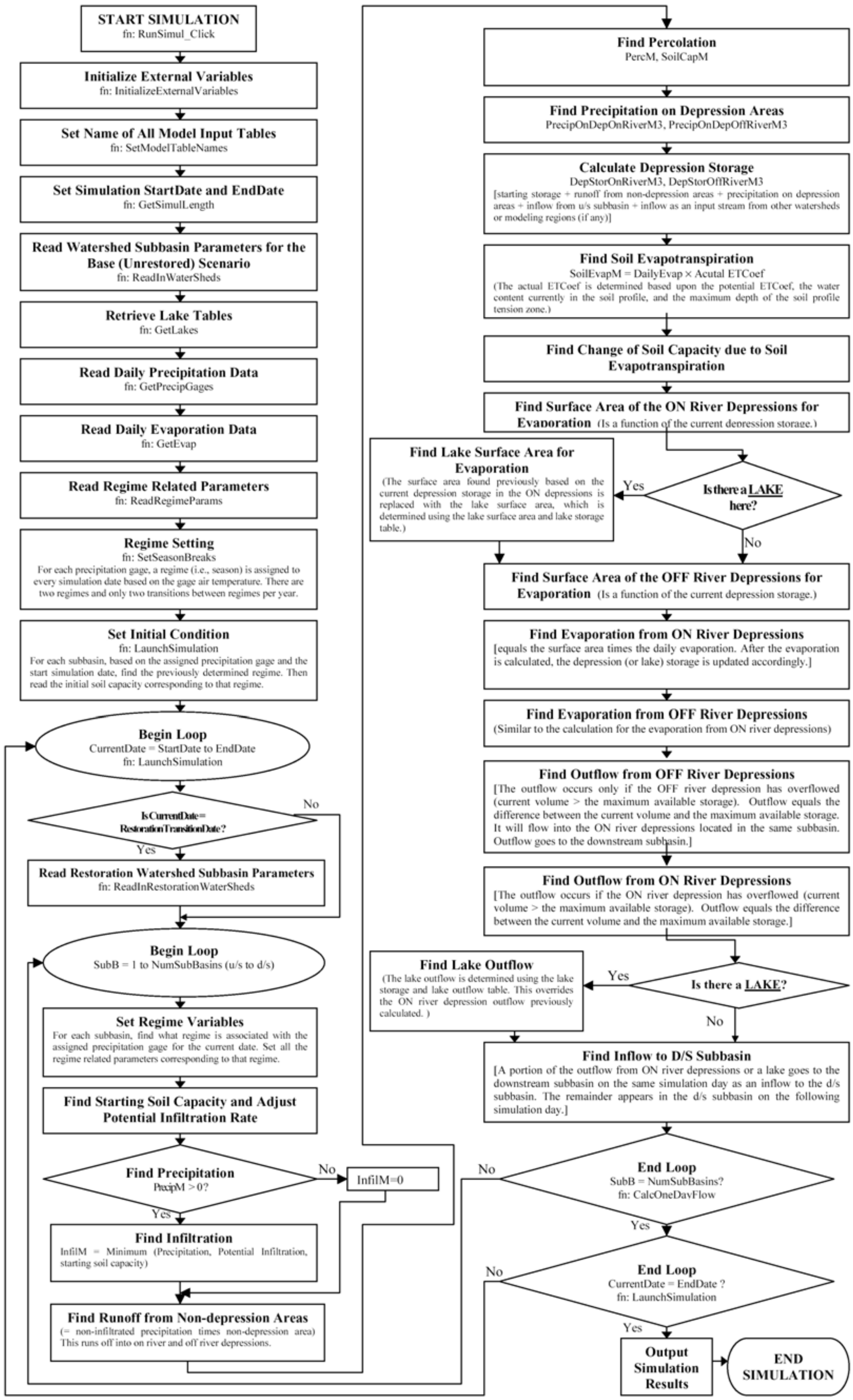

Figure 5. PRINET Flow Chart

There were 9,078 subbasins modeled in the upper basin and the average subbasin area was 0.29 square miles. The subbasins in each subwatershed were networked; that is, the exact sequence of flow between subbasins was specified for each subwatershed. **Figure 6** shows and sample of the **PRINET** wetlands with their contributing drainage area and pour points.

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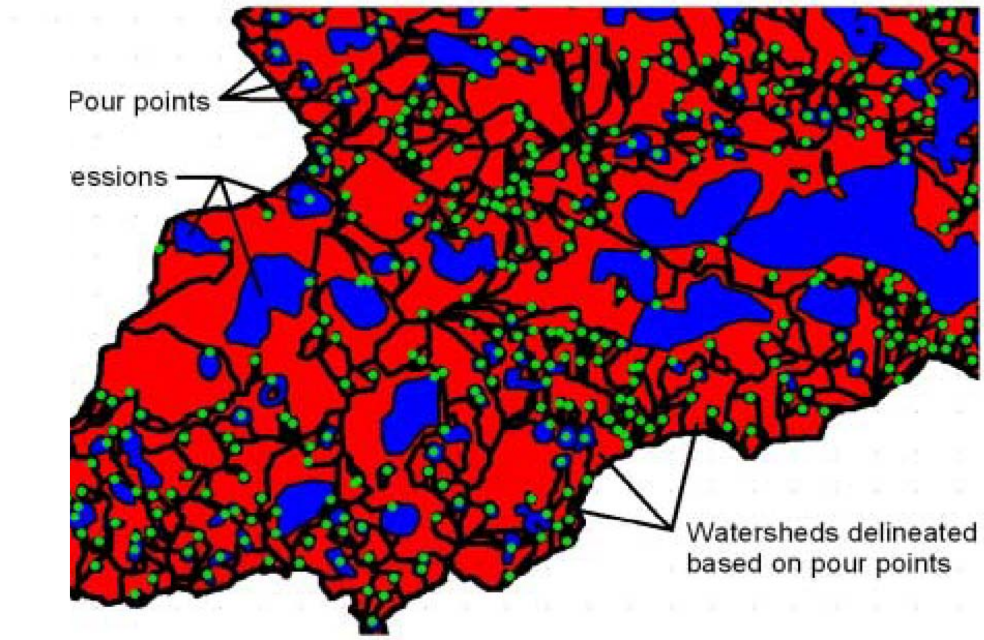

Figure 6. **PRINET** Subbasins and Pour Points

The computational sequence and the hydrologic processes modeled are summarized below. The model performs the following ten computations on daily basis:

1. Determine precipitation and evaporation for each day.

2. Add precipitation to the soil moisture and to the depressions.

3. Determine infiltration of precipitation into the soil, and update the soil moisture level accordingly.

4. Any precipitation that does not infiltrate runs off into intact depression storage. A separate accounting is made of on-river depressions (those that intersect the river network) and off-river depressions (those that do not intersect the river network).

5. If upstream subwatersheds exist, they are modeled as sources of flow into the downstream subwatershed model at the appropriate location.

6. Evaporation is calculated for each subbasin's intact depressions and the water storage volume is reduced accordingly.

7. Evapotranspiration is calculated for each subbasin's soil and the moisture level is reduced accordingly.

8. Percolation is determined for subbasins where the soil is sufficiently saturated to permit percolation.

9. When the depression water volume of a subbasin's off-river depression storage exceeds the off-river depression storage capacity, the excess runs off into the on-river intact depression storage of the same subbasin.

10. When depression water volume of a subbasin's on-river depressions exceeds depression storage capacity, the water flows into the intact on-river depression storage of the next downstream subbasin, or to the outlet of the subwatershed if there are no downstream subbasins.

Hydrologic Model Calibration

The **PRINET** model was calibrated to historic streamflows. The Devils Lake upper basin was divided into 12 different regions for calibration based on subwatershed boundaries and the location of streamflow gages. Since wetland drainage was allowed before the implementation of the wetland conservation provisions (i.e., "Swampbuster") in 1985, the amount of intact depression storage would be different before and after 1985. Therefore, the **PRINET** model calibration period was conducted for water years 1985 through 1999, a period with minimal changes to the depression topography and drainage network found in the upper basin. However, in order to provide a sufficient warm-up period, the model runs started on October 1, 1978 (start of water year 1979).

The overall calibration approach included the following primary objectives: (1) matching the total computed and observed volumes to within approximately one to two percent for the entire calibration period (1985-99), and (2) matching the pattern of dry, low runoff years in the late 1980s and the wet, high runoff years in the mid-to-late 1990s. The same hydrologic parameters were used for the entire calibration period; no parameters were varied annually to account for year-to-year differences. The number of parameters varied by calibration region was kept to a minimum.

Alternative Analysis

Eleven climatic scenarios were used to simulate future conditions with and without depression restoration. Possibly drained depressions having an average depth of greater than or equal to 0.5 feet were candidates for restoration. There were 13,464 restoration candidates (26 percent of the total number of possibly drained depressions) having a total surface area of 79,762 acres (86 percent of the total possibly drained depression surface area) and a total volume of 127,835 acre-feet (96 percent of the total possibly drained depression volume). Different levels of restoration (25, 50, 75, and 100 percent by volume of the restoration candidates) were analyzed.

Depressions were restored in each subwatershed. Each subwatershed had the same percentage of restored volume as the corresponding restoration scenario. For example, for 50 percent restoration (Scenario C), 50 percent by volume of the possibly drained depressions from Comstock was restored and 50 percent by volume of the possibly drained depressions from Starkweather was restored and so forth for each subwatershed.

The scenarios were constructed by **randomly** selecting depressions that had been classified as possibly drained and converting these depressions to possibly intact. The selection process was not optimized by drainage area or location. To construct the 25 percent restoration scenario model (Scenario B), enough restoration candidate depressions were randomly chosen in each subwatershed modeled until 25 percent of the total volume of restoration candidates was achieved for that subwatershed. These were converted to possibly intact depressions. To construct the 50 percent restoration scenario model (Scenario C), additional depressions, randomly selected, were added to this set until 50 percent of the total restoration volume was achieved for each subwatershed. The 100 percent restoration scenario (Scenario E) models had all restoration candidates reclassified as possibly intact.

The surface area and volume of the restored depressions for the different restoration levels are summarized in **Table 2.**

Table 2. Surface Area & Volume for Each Restoration Level

Restoration Level	25% (Scenario B)	50% (Scenario C)	75% (Scenario D)	100% (Scenario E)
Area Restored, acres	19,472	39,681	59,872	79,762
Volume Restored, acre-ft	31,431	63,608	94,850	127,835

When a depression was restored, the total depression volume to the pour point was restored. Though not considered in this study, additional volume could be retained in each depression by constructing berms, gated structures, or tiebacks to higher ground. Since the contributing drainage areas are modeled for each of the depressions, only the runoff from the area that drains to the depression fills the depression. Some depressions may have large contributing areas that may cause overtopping whereas some depressions may not. Depending on the depression surface area and evaporation rate, the amount of storage carry-over from year to year will vary with the depression characteristics. Generally, the annual available depression storage is less than the total depression storage.

The annual flow reductions resulting from depression restoration vary significantly for individual water years. In dry years, the percent of flow reduction is larger than in wet years. **Table 3** shows the average annual flow reduction for each restoration scenario and climate sequence. The average annual runoff reduction is less than the restored volume.

One method of presenting the impact of restoration on runoff reduction is by evaluating the ratio of the reduction in annual runoff volume to the area restored. For example, for the 25 percent restoration level (B), the average runoff reduction is 6,826 acre-ft. Since 19,472 acres were restored, this yields 6,826 acre-ft / 19,472 acres = 0.35 feet = 4.2 inches. This value primarily represents the difference between storage and evaporation in the restored depressions and the percolation and evapotranspiration from the soil area before restoration. It does not represent the average evaporation from a depression, which was approximately 20 or more inches per year.

The **PRINET** model did not include a soil moisture algorithm beneath the depressions. Instead, the depressions were modeled as hard-bottom “bowls”. Consequently, infiltration of water from a depression into the soil and evapotranspiration from the soil in the dry portions of a depression (when the depression was less than 100 percent full) were not modeled. Therefore, the model could be under predicting the net total evaporation (free surface evaporation plus evapotranspiration from the soil) in the depressions.

Table 3. Average Annual Flow Reduction

		No Restoration		Restoration Level			
				25% (B, 31,431 acre-ft and 19,472 acres restored)	50% (C, 63,608 acre-ft and 39,681 acres restored)	75% (D, 94,850 acre-ft and 59,872 acres restored)	100% (E, 127,835 acre-ft and 79,762 acres restored)
Climate Sequence	Water Years	Total Runoff (acre-ft)	Average Annual Runoff (acre-ft)	Average Annual Runoff Reduction (acre-ft)			
001	2003-2020	3,101,720	172,318	7,294	14,007	20,754	27,173
002	2003-2020	2,017,254	112,070	7,058	13,496	18,737	23,702
003	2003-2020	1,688,607	93,812	6,714	12,653	17,729	23,056
004	2003-2020	1,292,294	71,794	6,150	11,704	16,909	21,638
005	2003-2020	2,888,905	160,495	7,869	15,246	22,303	29,533
006	2003-2020	1,279,228	71,068	5,661	10,185	14,174	18,291
007	2003-2020	2,259,557	125,531	7,395	14,013	19,727	25,404
008	2003-2020	1,594,247	88,569	6,601	12,802	18,098	23,328
009	2003-2020	1,632,394	90,689	7,151	12,881	18,089	23,545
010	2003-2020	2,051,472	113,971	6,464	12,111	17,511	22,745
Average		1,980,568	110,032	6,836	12,910	18,403	23,841
As Percent of Restored Volume				22%	20%	19%	19%
Runoff Reduction Volume / Area Restored				4.2 in	3.9 in	3.7 in	3.6 in
WET	2003-2035	8,737,679	264,778	7,959	15,643	23,502	31,193
As Percent of Restored Volume				25%	25%	25%	24%

Given the current classifications of "possibly intact" and "possibly drained" depressions, the runoff reduction values reported in this study are conservative for two reasons:

- The depressions restored in the 25, 50, and 75 percent restoration scenarios were selected randomly within each subwatershed. The restoration level was uniform across all subwatersheds (e.g., for the 25 percent restoration scenario, 25 percent by volume of the restoration candidates in the Comstock subwatershed was restored, 25 percent by volume of restoration candidates in Edmore was restored, and so forth for each subwatershed). Incremental optimization of the depressions selected for restoration was not performed. It is expected that the runoff reduction volumes would increase for the scenarios having less than 100 percent restoration if the restoration candidates were selected using an optimization routine (i.e., determine which depressions would result in the largest runoff reduction). Potential optimizations include selection by contributing drainage areas, by location (restoring depressions in subwatersheds having high runoff and a larger percentage of "possibly drained" depressions or restoring on-river depressions before off-river), and by depression size or volume.

- Since the net total evaporation from the depressions was probably underpredicted, the annual runoff reduction with depression restoration could be underestimated.

Future Studies

Since the results of this study indicate that depression restoration can reduce the volume of runoff entering Devils Lake, further studies should be conducted to more accurately quantify the runoff reduction resulting from depression restoration. The recommendations for the refinement of the depression delineation and classification were discussed previously.

The hydrologic model, **PRINET**, was developed in accordance with the study goals to simulate soil and depression storage in the Devils Lake basin. Some simplified algorithms for depression storage and evaporation, snowmelt and frozen ground were incorporated into the model. These algorithms were appropriate for this study. However, the following model refinements are recommended for more detailed analyses:

- The **PRINET** model did not include a soil moisture algorithm beneath the depressions. Instead, the depressions were modeled as hard-bottom "bowls". Consequently, infiltration of water from a depression into the soil and evapotranspiration from the soil in the dry portions of a depression (when the depression was less than 100 percent full) were not modeled. Therefore, the model could be underpredicting the net total evaporation (free surface evaporation plus evapotranspiration from the soil) in the depressions. A soil moisture accounting algorithm with infiltration and evapotranspiration should be added to the model.

- The Devils Lake evaporation was applied to the depression. Since the depressions are significantly smaller water bodies, the depression evaporation may differ from the Devils Lake evaporation. Some evaporation measurements for different depression sizes would be useful in determining the rate of evaporation from the depressions compared to pan evaporation measurements and the evaporation from Devils Lake.

- A relationship of surface area versus storage was developed for the depressions. This relationship was in the envelope of area-storage curves provided for several of the upper basin lakes. The digital elevation models could be used to refine the area-storage relationships of the depressions.

- The degree-day method was used to simulate snowmelt in **PRINET**. A more rigorous energy budget algorithm could be developed if the required data are available.

- An infiltration/season break was incorporated in the model to simulate frozen and unfrozen ground conditions (i.e., low and high infiltration conditions). A 30-day moving average of the average daily temperature is used to transition between the two conditions. The volume of runoff is very sensitive to the infiltration break. A more physically based algorithm should be incorporated into the hydrologic model.

If the hydrologic model is modified, the model must be re-calibrated to observed data before it is used to evaluate depression restoration.

For the restoration scenarios with less than 100 percent depression restoration, the restoration candidates were selected randomly within each subwatershed. Incremental optimization of the depressions selected for restoration was not performed. It is expected that the runoff reduction volumes associated with depression restoration would increase if an optimization routine were used to select the depressions for restoration. Potential optimization parameters are contributing drainage area, depression location, and depression size or depression volume.

References

WEST Consultants, INC.& Polaris Group, Final Report, Devils Lake Upper Basin Storage Evaluation, San Diego, CA, 30 April, 2001.